Microsyst Technol (2007) 13: 305–310
DOI 10.1007/s00542-006-0181-4

TECHNICAL PAPER

Albert Albers · Norbert Burkardt · Tobias Deigendesch
Jochen Marz

Micro-specific design flow for tool-based microtechnologies

Received: 31 August 2005 / Accepted: 20 January 2006 / Published online: 26 September 2006

Abstract Design of systems and components being produced with tool-based microtechnologies is strongly driven by technology. Thus, there are multitechnological influences from production, materials or micro-specific effects, which restrictively affect design and have to be considered. Under special regard of these peculiarities and in context with live cycle stages of tool-based microtechnological products, a design flow is presented. This incorporates a new design model, called sickle model visualizing the specific aspects when designing products of tool-based microtechnology. In order to support the design process, design rules are used to transfer knowledge from subsequent and adjacent life cycle stages to the current design stage.

1 Introduction

Tool-based microtechnology, i.e. primary shaping of micro parts, is increasingly investigated. When designing tool-based micromachined products, technology has strong influences on product development (Albers et al. 2003; Marz et al. 2004). Up to now product development processes in tool-based microtechnology were not considered. Also the characteristics of such a process were both not identified and described. Assuming mass-production in future, deeper understanding of the development process of primary-shaped micro parts is essentially required in order to realize consistent product designs. Due to the fact that early decisions in product development have high impact on subsequent stages, transfer of knowledge from these stages to early stages has to be enabled by integration of means of knowledge management. One instrument for knowledge provision in early development stages is the utilization of design rules.

At first this paper presents aspects that influence micro-specific design. Then the development process and the design stage within the product life cycle are highlighted under special regard of micro-specific influences. Further on the specific design flow for tool-based microtechnology is discussed. Finally design rules as a means of support are presented.

A. Albers (✉) · N. Burkardt · T. Deigendesch · J. Marz
Institute of Product Development Karlsruhe (IPEK),
University of Karlsruhe (TH), 76128 Karlsruhe, Germany
E-mail: albers@ipek.uni-karlsruhe.de
Tel.: +49-721-6082371
Fax: +49-721-6086051

2 Micro-specific design aspects

Established microtechnologies are Silicon micromachining, the LIGA process and mechanical micromachining. Silicon micromachining and LIGA are called mask-based technologies, since substantial structuring steps are performed by exposure to radiation through a patterned mask.

Mechanical micromachining technologies are tool-based microtechnologies, which derive from miniaturization of conventional manufacturing processes, such as separative (e.g. milling), erosive (e.g. electro discharge machining) or laser ablative processes as well as primary-shaping (e.g. injection molding) or forming processes. For the latter microstructured master models, foundry patterns or mold inserts are required.

By offering the possibility of shaping the third dimension and utilizing it as a working surface relevant to function, tool-based microtechnologies and LIGA enable load bearing and transmitting systems. A unique feature of tool-based microtechnologies is the possibility to realize complex three-dimensional structures or even free-form surfaces. However, although tool-based microtechnologies provide a greater freedom of design regarding shape and applicable materials than other microtechnologies, there are technological conditions and restrictions that have to be stringently considered when designing microsystems. Such restrictions are e.g. achievable flowlengths, aspect ratios or minimum wall thicknesses. This results in a strong orientation on what is producible and—in contrast to macroscopic product design, which is driven by market requirements—in a technology-driven design approach. These influencing multitechnological conditions and restrictions derive from production, material and micro-specific effects (Marz et al. 2003). In order to realize a design compatible to production, specific knowledge from subsequent product life cycle stages has to be incorporated into the product design flow. Thus design rules, i.e. compulsory instructions, are introduced as a methodological aid for designers (Albers and Marz 2003).

3 Micro-specific product development

Established design flows of macroscopic development processes and those of established microtechnologies were analysed and evaluated with respect to application to design tool-based micromachined systems. The evaluation of these design flows resulted in requirements, which had to be fulfilled by the design flow for tool-based microtechnologies. Such requirements were, e.g. control of the technology-driven process or market-orientation. Based on these requirements and on the experience the authors made while designing tool-based micromachined products, a micro-specific design flow was established. (Marz 2005)

4 Design in the context of product life cycle

In order to understand the design flow and its influencing surroundings, i.e. subsequent and adjacent stages, the product life cycle had to be investigated. Figure 1 shows the life cycle stages for a tool-based micromachined product. The stages are not passed absolute serially, but partial parallelly with more or less strong interaction. For market success, the interacting factors customer, competition, technology and producer have to be considered.

Within the product profile stage, general product features are defined without specification of technological or creative parameters. Strategic freedom, customer demands and market trends define target fields. The following task is to fill these target fields with product ideas. When constituting the system of objectives, all objectives and their interactions are defined. This step is required in order to concretize the design task and to clarify vague demands to the object system, i.e. the subsequent microproduct. Thus, the system of objectives represents a mandatory and structured constitution of the target features of the object system, which has to be created. Based on the specification of the system of objectives, the operation system *development*, i.e. the design itself, develops the *development* object system, which corresponds to the system of objectives of the subsequent production process (cp. Fig. 2).

During the detailing stage, on the one hand all items related to design, i.e. the *development* object system, are documented. On the other hand production specifications are composed, which represent the *production* system of objectives. Aspects of the *development* object system are, e.g. 3D CAD models, assembly drawings or dimensioned drawings. Thus the resulting aspects of the *production* system of objectives are for example oversized 3D CAD models of a green body for sintering. Using appropriate CAD-CAM-interfaces, mold designs can be derived for process preparation.

Following the development process there are stages of process preparation (e.g. manufacturing of molds) and of production (e.g. powder injection molding) in order to achieve the final product components. Validation and prototyping stages accompany the stages from design to production. If microsystems ever will be recycled is not foreseeable (dashed box in Fig. 1).

Most influences affecting micro-specific design can be traced back to subsequent stages of process preparation and production. Those mostly restricting influences are the cause of the technology-driven design flow. These influences, technological conditions, limiting factors and restrictions are detected. Based on that, limiting specifications for realizable structures are identified and provided as design rules as a means of support for designers.

5 Design flow

Unlike known in conventional design flows, designing of the system, of its components and of structural details has to be done parallelly (cp. Fig. 3). While the system is conceptually designed, components are designed basically. At the same time structural details have to be designed precisely due to the strong influence of tool-based microtechnology. These structural details are determined by restrictions from production technologies, from materials and effects and are invariant from the beginning of the design stage. Thus the designer is supported by an external knowledge representation, which describes technological facts. In this case design rules are used to describe knowledge regarding technological conditions, limiting factors and restrictions, e.g. minimum widths, distances or roundings. Then basic design of the system and detail design of components takes place. Eventually, the system is designed precisely. Obviously, the design flow features a parallelization of function-oriented decisions on system level (top-down) and technology-driven detail design on structural level (bottom-up). Thus it appears that the design flow embarks on a meet-in-the-middle-Strategy: The continually changing of the point of view between the overall system and structural details.

The special aspects of designing tool-based micromachined systems are visualized by the sickle-model (cp. Fig. 4). Due to the sickle-shaped transition from the

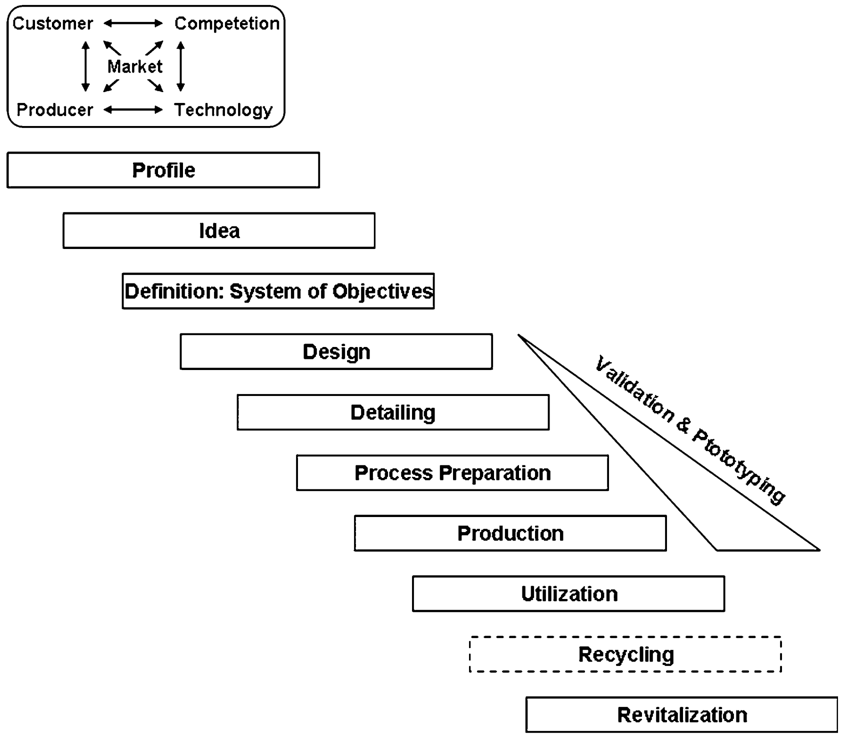


Fig. 1 Life cycle stages for products made with tool-based microtechnologies

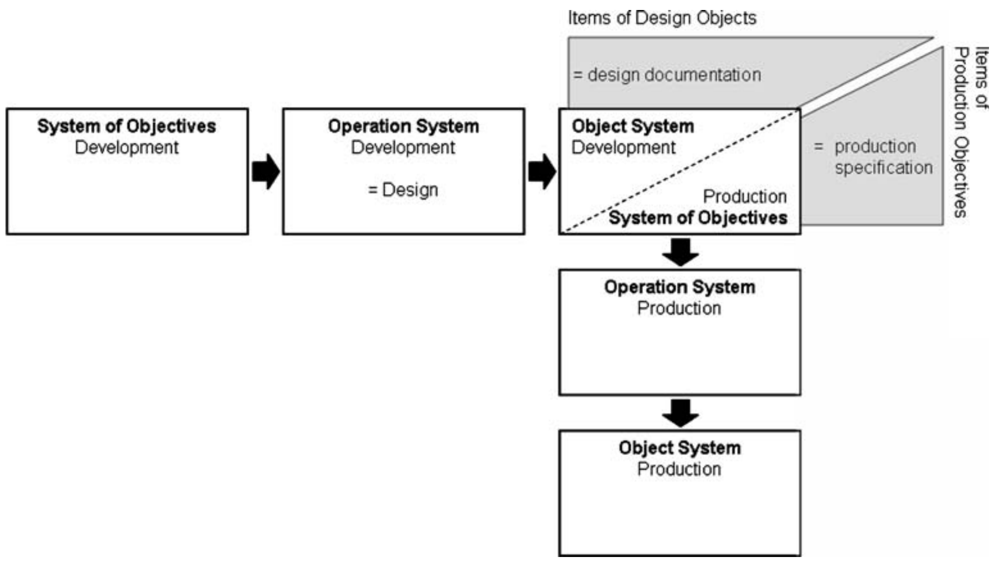


Fig. 2 Correlation of the system of objectives, of the operation system and object system

design stage to the detailing stage the name *sickle-model* is introduced.

The model presents the design stages (cp. Fig. 3) on different levels of abstraction. It incorporates the three levels of abstraction *structure*, *component* and *system* as well as the design stages *conceptual*, *basic* and *detail design*.

These three levels of abstraction are represented by three concentric rings, whereas the level of abstraction increases from the inner to the outer ring. The model shown in Fig. 4 describes the universal case of a complex and comprehensive microsystem. Of course, it is imaginable to use only one level of abstraction for simple designs, e.g. specimens featuring a constant cross-section. The number of levels of abstraction being required is set by the definition of the system of objectives.

The design stages *conceptual*, *basic* and *detail design* are arranged counterclockwise tangentially becoming more concrete. Design activity itself is a superposed flow. The superposition of bottom-up design from structural level to system level and the top-down process

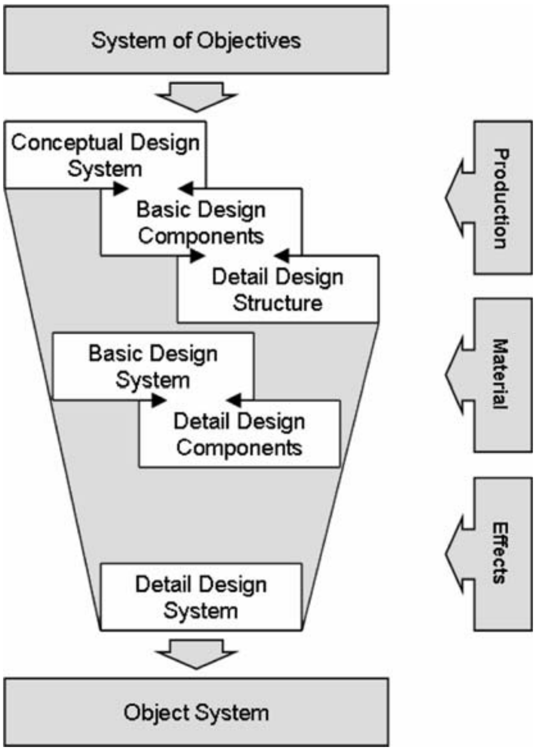


Fig. 3 Design stages

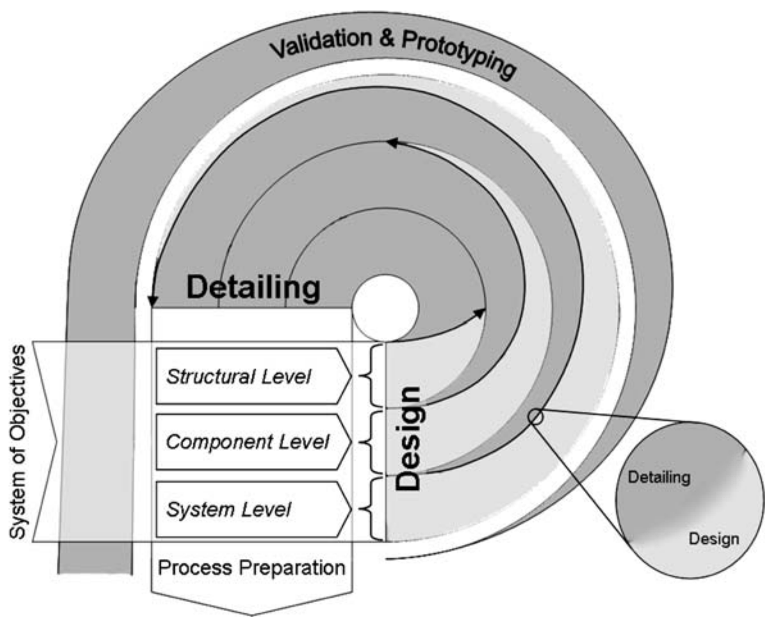
from conceptual design to detail design results in a global sickle-curve.

This global sickle-shaped process completely characterizes design. Assuming again a simple design, e.g. a specimen, for whose design a single level of abstraction, e.g. component level, is sufficient, the global sickle-curve is in coincidence with the actual, local sickle-curve. In case of a complex system design including all levels of abstraction the global sickle-curve is separated into three local sickle-curves for the structural, component and system level. The sickle-model is created iteratively on purpose. Thus, in case of a suboptimal result, the designer can perform another iteration loop.

For describing the transition from function to embodiment, the junction of design and detailing has to be regarded (cp. Fig. 4, magnified extract). Therefore a "methodolocial stage of transition" is introduced. From a development point of view the designer approaches with the results of conceptual design on system level. Based on the system of objectives main function and sub-functions are extracted. Now, supported by methodological means, e.g. effect catalogues, the designer looks for effects (working principles) that fulfil these sub-functions. Combining these partial solutions results in a conceptual design, which incorporates abstract functional items and basic shapes without respect to material assignment or quantified dimensions. The system itself is divided into components roughly. The functional items are now treated on structural level. Structural details for the functional items are designed under special regard of technological conditions and restrictions. The latter are provided by an external knowledge representation. Therefore design rules are used, which represent knowledge, e.g. from process preparation, in terms of realizable structural details. These structural details are concrete design features, like minimum widths, distances or roundings deriving from tools, machine tools, process or process flow. The combination of invariant structural details derived from design rules and imaginable structural details deriving from functions takes place on the "methodological stage of transition".

This shall be clarified by designing a tooth of a gear wheel. The gear system was conceptually designed on

Fig. 4 Sickle-model for design in tool-based microtechnology



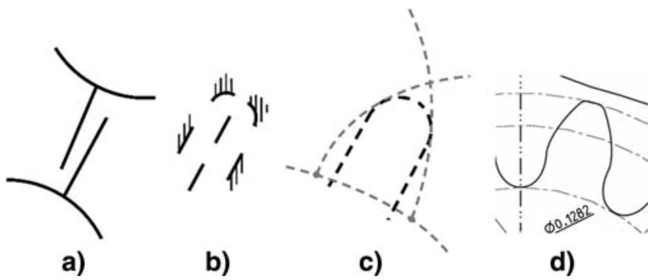


Fig. 5 Designing structural details based on functional items (b)

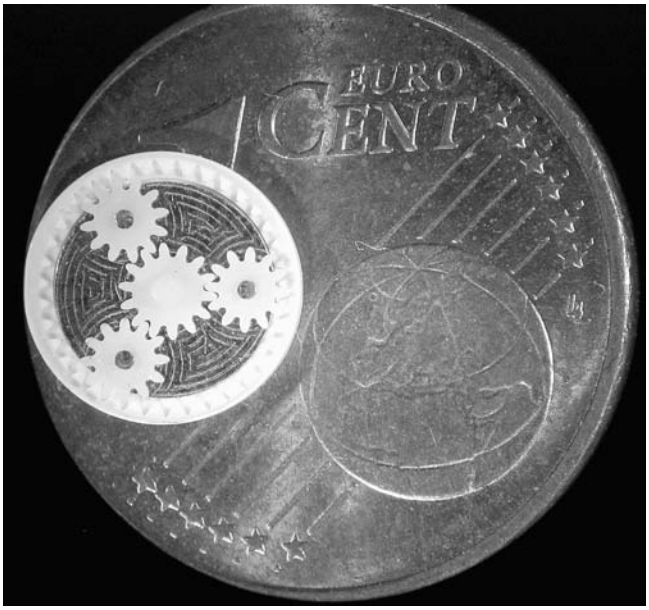


Fig. 6 Planteray gear developed with the micro-specific design flow

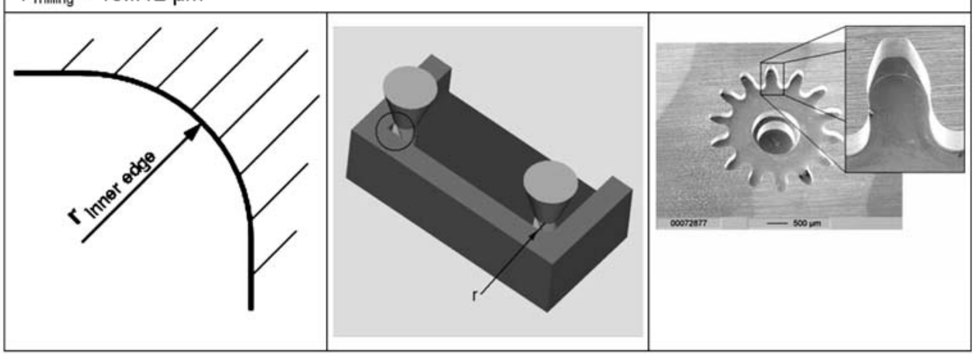
system level and was roughly divided into components. Now the function item "tooth" shall be designed on structural level. Figure 5a presents an abstract illustration of the tooth without any assignment of material or dimensions. For functioning, the tooth needs a finite tooth depth, tooth thickness and face width (cp. Fig. 5b). Imagining the mold insert, it is obvious that a certain space for the milling tool is required (cp. Fig. 5c). When finalizing the design, this design feature results in a distinctive tip rounding of the tooth (cp. Fig. 5d) due to the radius of the milling cutter (cp. Fig. 6). Thus the "methodological stage of transition" is required to adhere to invariant structural details while synthesizing by a creative thinking process.

6 Design rules

Within a technology-driven design flow, the designer needs certain knowledge about production technology, which usually is reserved to production specialists. Within established domains of microtechnology, e.g. microelectronics, silicon micromachining or LIGA, design rules represent an approved means feeding production knowledge back to the design stage (Mead et al. 1980; Leßmöllmann 1992; Scherer et al. 1996; Hansen et al. 2002; Rabaey et al. 2003; Solf et al. 2003). However, the term "design rule" is not used consistently in these domains. Thus an own definition is required: Design rules are instructions based on technological conditions and restrictions that have to be respected compulsorily in order to achieve a realizable design. In short: Design rules are compulsory instructions. In this context "technological conditions and restrictions" mean all conditions and restrictions deriving from pro-

Fig. 7 Design rule for a geometrical restriction from micro milling

KR_MF3_x_001
Minimum radius for vertical inner edges
All vertical edges parallel to the milling cutter's axle have a minimum radius due to the tool's shape. The value of the radius consists of half the milling cutter's body diameter plus the tolerances from the machine tool and the process control.
$r_{\text{inner edge}} \geq r_{\text{min}} = ½ \cdot d_{\text{milling cutter, min}} + T_{\text{milling}}$
$d_{\text{milling cutter, min}} = 100\ \mu m$ $T_{\text{milling}} = 10...12\ \mu m$



cess preparation, production and material behaviour. These design rules form a methodological aid for realizing a transfer of knowledge from the operation system *production* to the operation system *development*.

As an example the production of a micro gear wheel by powder injection molding with a subsequent sintering process is used. This requires a mold insert, which is manufactured by micro milling within the process preparation stage. Due to the circular cross-section of the milling cutter, all vertical inner edges feature a minimum edge rounding radius plus the milling tolerances (cp. Fig. 7) (Deigendesch 2004). When designing the mold insert for the gear wheel the tip of the tooth gets a tip edge rounding of at least half of the diameter of the milling cutter. This detailed design feature is determined at the beginning of the design process and is kept invariant to the end, i.e. to the final detail design of the entire system.

For deriving design rules from technological processes a procedure was developed (Albers and Marz 2004). At first, potential influences of a technology on micro-specific design are detected. Features of this technology are extracted in a preferably quantifiable way. These extracted properties have to interpret in a way relevant to design, i.e. projected on possible component and system structures. This knowledge is now being transformed to knowledge being applicable for designers. Hereupon transformed knowledge is formulated in universally valid design rules, which are classified and filed. Providing of design rules is enabled by both an interactive knowledge portal, called design and methodology database, and a knowledge-based engineering environment (Albers et al. 2005).

7 Summary and conclusion

This paper discussed the micro-specific design flow for tool-based microtechnology. Based on analysis of established product development processes a micro-specific design flow was created. A principal item of this process model is the sickle-model, which describes design action illustratively. This model is combined with an external knowledge representation, design rules.

The sickle-model combines both bottom-up design from structural to system level and top-down design from conceptual to detail design. This results in a meet-in-the-middle strategy as an optimal strategy for designing products based on tool-based microtechnology.

Acknowledgements We are grateful for the support provided by the German Research Foundation (DFG) within the collaborative research center 499 “Development, production and quality assurance of primary shaped micro components from metallic and ceramic materials”.

References

Albers A, Marz J (2003) Knowledge-based design environment for primary shaped micro parts. In: 5th international workshop on high aspect ratio micro-structure technology, HARMST 03

Albers A, Marz J (2004) Restrictions of production engineering on micro-specific product development. Microsyst Technol 10:205–210

Albers A, Marz J, Burkardt N (2003) Design methodology in micro technology. In: 14th international conference on engineering design, ICED 03

Albers A, Burkardt N, Hauser S, Marz J (2005) Knowledge-based engineering environment for primary shaped micro parts. Microsyst Technol 11:254–260

Deigendesch T (2004) Konstruktionsregeln als methodisches Hilfsmittel zur durchgängigen Unterstützung des Entwurfsprozesses in der Mikrotechnik. University of Karlsruhe (TH) diploma thesis

Hansen U, Germer C, Büttgenbach S, Franke HJ (2002) Rule based validation of processing sequences. In: 5th international conference on modeling and simulation of microsystems, MSM2002

Leßmöllmann C (1992) Fertigungsgerechte Gestaltung von Mikrostrukturen für die LIGA-Technik. University of Karlsruhe (TH) doctoral thesis

Marz J (2005) Mikrospezifischer Produktentwicklungsprozess (μPEP) für werkzeuggebundene Mikrotechniken. In: Albers A (ed) Forschungsberichte des Instituts für Produktentwicklung, Vol.17 (University of Karlsruhe (TH) doctoral thesis)

Marz J, Burkardt N, Albers A (2003) Methodological investigation of the product development in micro technology. In: 4th international topic conference, EUSPEN 03

Marz J, Burkardt N, Albers A (2004) Methodisch unterstützter Entwurf mechanischer Mikrosysteme. ETG-/GMM-Fachtagung: Innovative Klein- und Mikroantriebstechnik, VDE, Berlin: 63–67

Mead C, Conway L (1980) Introduction to VLSI systems. Addison-Wesley, Reading

Rabaey JM, Chandrakasan A, Nikolic B (2003) Digital integrated circuits—a design perspective, 2nd edn. Prentice Hall, New Jersey

Scherer KP, Buchberger P, Eggert H, Stiller P, Stucky U (1996) Knowledge based support for manufacturing of microstructures. Microsyst Technol 2:167–170

Solf C, Janssen A, Mohr J, Ruzzu A, Wallrabe U (2003) Incorporating design rules into the LIGA technology applied to a Fourier transformation spectrometer. Book of Abstracts HARMST ‘03